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AGN Physics from QSO Clustering

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Abstract. We review the current status of QSO clustering measurements, particular with respect to their relevance in understanding AGN physics. Measurements based on the 2dF QSO Redshift Survey (2QZ) find a scale length for QSO clustering of $s_0 = 5.76^{+0.17}_{-0.27} h^{-1}$ Mpc at a redshift $\bar{z} \simeq 1.5$, very similar to low redshift galaxies. There is no evidence of evolution in the clustering of QSOs from $z \sim 0.5$ to $z \sim 2.2$. This lack of evolution and low clustering amplitude suggests a short life time for AGN activity of the order $\sim 10^6 - 10^7$ years. Large surveys such as the 2QZ and SDSS also allow the study of QSO environments in 3D for the first time (at least at low redshift), early results from this work seem to show no difference between the environments of QSOs and normal galaxies. Future studies e.g. measuring clustering as a function of black hole mass, and deep QSO surveys should provide further insight into the formation and evolution of AGN.

1. Introduction

Analysis of the space distribution of QSOs provides an important test of models of AGN formation. Large surveys such as the 2dF QSO Redshift Survey (2QZ;

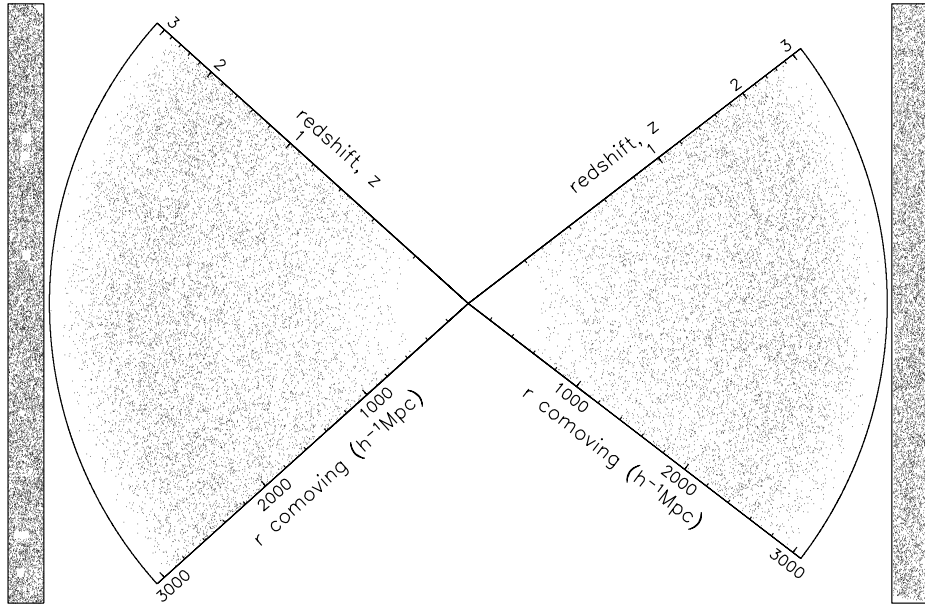


Figure 1. The distribution of QSOs in the final 2QZ catalogue, showing the Southern (left) and equatorial (right) strips. The rectangular regions show the projection onto the sky. An Einstein-de Sitter cosmology was assumed in calculating the comoving distances to the QSOs.

Croom et al. 2001) and SDSS (Schneider et al. 2002) provide the first opportunity to make accurate measurements of the clustering properties of AGN. Previous samples were too small and/or inhomogeneous to make anything other than a detection of the clustering signal (e.g. La Franca et al. 1998; Croom et al. 1996; Shanks et al. 1987; Osmer 1981). However, with homogeneous samples in excess of 20000 objects, the predictions of QSO formation models can be directly tested. Because of the high redshift and large volume that QSOs can sample, they are also a powerful probe of large-scale structure which can be used to answer cosmological questions, such as the values of fundamental cosmological parameters. However in this review we will concentrate on what we can learn about the physics of AGN from clustering measurements.

Under the standard paradigms of structure formation, the strength of QSO clustering is directly related to the mass of the dark matter halo in which the QSOs reside. At a given redshift, the most massive dark matter halos will be clustered more strongly than less massive halos. Thus QSO clustering measurements should enable us to determine in a statistical sense the mass of the dark matter halo containing QSOs and their host galaxies. For a given underlying matter power spectrum the expected number density of dark matter halos can be derived (Press & Schechter 1974), and then comparisons to the number density of QSOs (the QSO luminosity function) can be used to determine the fraction of active galaxies at any given time, and hence the typical lifetime of activity.

Cross-correlation with other sources (e.g. 'normal' galaxies) also allows us to discover something about the environments of QSOs. This could lead to a clearer understanding of the triggering mechanisms for activity (e.g. mergers).

In this short review we will look at the current status of QSO clustering measurements and QSO environmental studies. We will conclude with a discussion of some of the outstanding issues and potential ways forwards.

2. The current status of QSO clustering

To date the most detailed clustering analysis of QSOs has been carried out using the 2QZ sample which contains over 20000 QSOs. Compiled using the 2-degree Field (2dF) instrument on the Anglo-Australian Telescope (Lewis et al. 2002), this survey obtained redshifts for QSOs at $z < 3$ with $16 < b_J \leq 20.85$ mag. The relatively faint magnitude limit of the 2QZ means that the surface density of QSOs found is $\sim 35 \text{ deg}^{-2}$, much higher than most other QSO surveys. This high density of QSOs makes the 2QZ a powerful probe of large-scale structure. The spatial distribution of QSOs in the 2QZ is shown in Fig. 1.

The most basic of clustering measurements is the two-point correlation function, $\xi(s)$ (or its Fourier transform the power spectrum, $P(k)$), where s is the separation of QSOs in redshift-space. This is shown in Fig. 2 (left) for the 2QZ averaged over the redshift range $0.3 < z < 2.9$, assuming $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ (which we will call the Λ cosmology). The measured $\xi(s)$ is very similar to that found for low redshift galaxy samples, (e.g. the 2dF Galaxy Redshift Survey, 2dFGRS; Hawkins et al. 2003) and the best fit power law is $\xi(s) = (s/5.76_{-0.27}^{+0.17})^{-1.64_{-0.03}^{+0.06}}$. We can also fit more physically motivated models, such as those based on CDM. In Fig. 2 we plot a linear CDM correlation function normalized such that normal galaxies are virtually unbiased at the present day (see Hawkins et al. 2003) (lower dotted line). The best fit CDM models have a shape parameter $\Gamma = 0.1$, with slightly more large-scale structure than standard models (but not significantly so). We also derive the non-linear corrections to these linear models based on the formalism of Peacock & Dodds (1996). It is worth noting that at the high redshifts probed by QSOs ($\bar{z} \simeq 1.5$) clustering remains linear even at relatively small scales, $\sim 5 h^{-1} \text{ Mpc}$. For a given cosmology, we can then derive the mean bias of the QSOs, $b_{\text{QSO}} \simeq 2$ at $\bar{z} \simeq 1.5$.

In Fig. 2 (right) we show the best fit clustering scale length s_0 (assuming a power law fit) as a function of redshift. We find that there is no significant evolution of clustering with redshift. The clustering amplitude of the QSOs is also consistent with that found in $z \sim 3$ Lyman-break galaxies (Adelberger et al. 1998). The data are also clearly inconsistent with linear evolution (solid line), and thus b_{QSO} must be a function of redshift. A simple model would be to assume that QSOs were cosmologically long lived objects with ages of order a Hubble time. In this case their bias would evolve as $b(z) = 1 + (b(0) - 1)G(\Omega_M, \Omega_\Lambda, z)$ where $b(0)$ is the bias at $z = 0$ and $G(\Omega_M, \Omega_\Lambda, z)$ is the linear growth rate of density perturbations. In this model the QSOs would be formed at some arbitrarily high redshift and move in the gravitational potential of the mass distribution. This model (dotted line) is ruled out at high ($> 99.99\%$) significance, demonstrating that QSOs must be short lived compared to the age of the Universe. A number of authors (e.g. Martini & Weinberg 2001) have

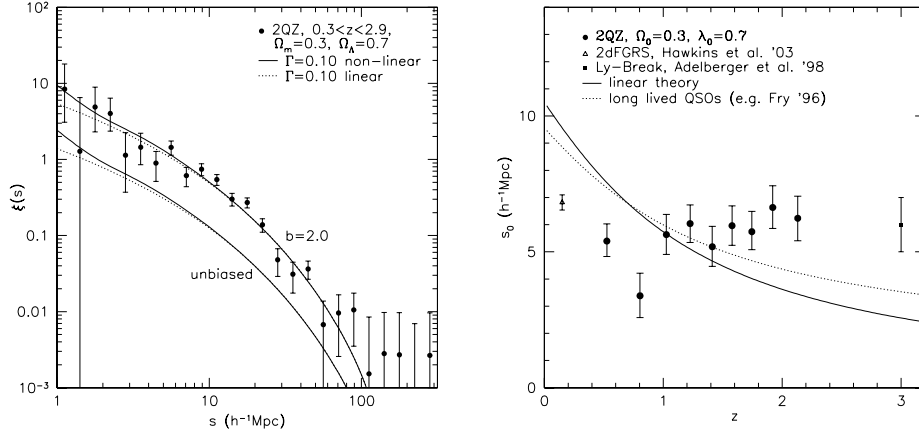


Figure 2. Left: $\xi(s)$ for QSOs from the 2QZ (filled circles) in a Λ Universe. Compared to this are linear (dotted lines) and non-linear (solid lines) CDM models with a shape parameter, $\Gamma = 0.1$. The lower lines are the mass correlation function normalized at low redshift by observations of the 2dFGRS. The upper lines are scaled by a factor of 4 ($b_{\text{QSO}} = 2$). Right: The scale length, s_0 , of QSO clustering as a function of redshift (filled circles) compared to the clustering of low (triangle) and high (square) redshift galaxies and two models assuming linear theory (solid line) or long lived QSOs (dotted line).

constructed more detailed models based on the Press-Schechter formalism to constrain the typical lifetime of QSOs via clustering measurements. Comparison to the current data suggest that QSO lifetimes, at least at $z \sim 2$ are $\sim 10^6$ years with typical halo masses of $\sim 10^{12} M_{\odot}$. Models which include the effects of gas and stars (e.g. see Di Matteo et al., this volume) increase the typical time scale, but only to $\sim 10^7$ years.

Another prediction of QSO formation models (e.g. Kauffmann & Haehnelt 2000) is that QSO clustering depends on luminosity. Only very marginal evidence has so far been found to support this (e.g. Croom et al. 2002), to fully test this prediction samples which span a broad range in luminosity at a given redshift are required.

3. QSO environments

Complementary to the above analysis is the study of QSO environments via the cross-correlation of QSOs and galaxies. Until very recently, this has only been possible using 2D angular clustering measurements (e.g. Ellingson, Yee & Green 1991; Smith, Boyle & Maddox 1995; Croom & Shanks 1999). These generally showed that radio-quiet QSOs were clustered similarly to normal galaxies, while radio-loud QSOs appeared in richer environments.

With new large QSO surveys such as the 2QZ and SDSS it is now possible to carry out cross-correlations in 3D, making use of the fact that major galaxy

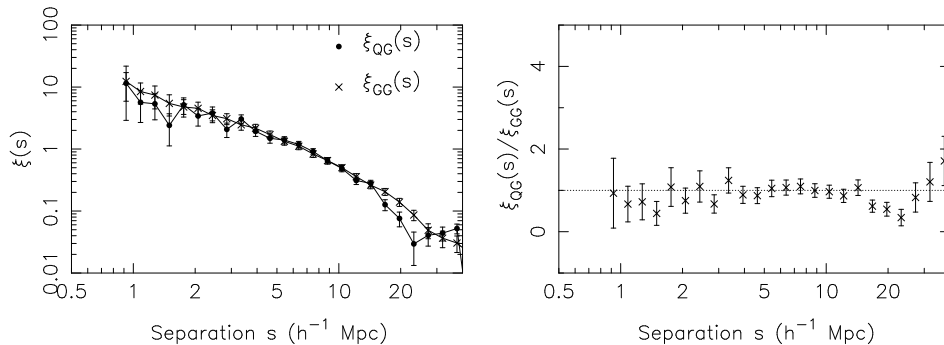


Figure 3. Left: The cross-correlation, ξ_{QG} , of 2QZ QSOs at $z < 0.3$ with galaxies from the 2dFGRS (filled points) compared to the auto-correlation, ξ_{GG} , of galaxies from the 2dFGRS. Right: the ratio of the two, ξ_{QG}/ξ_{GG} , as a function of scale.

surveys are being carried out in the same regions of the sky as the QSO surveys. The cross-correlations are limited to relatively low redshift, as these galaxy surveys typically probe $z < 0.3$, however the high quality photometry of SDSS should allow this to be extended to higher redshift via photometric redshifts.

We have measured the cross-correlation of QSOs from the 2QZ and galaxies in the 2dFGRS (Colless et al. 2001). This was carried out at $z < 0.3$ where galaxies are detected. This redshift also picks out the intrinsically faintest QSOs which will tend to lie at low z in any flux limited sample. The results are shown in Fig. 3. The cross-correlation between QSOs and galaxies is found to be identical to the auto-correlation of galaxies (weighted to have the same redshift distribution at the QSOs). If we divide the two measurements (Fig. 3 right) we determine a mean bias $b_{QG} = 0.97 \pm 0.05$. Thus it appears that the AGN are not clustered any differently to galaxies. Further work is clearly required to determine whether the bias between QSOs and galaxies is a function of QSO and/or galaxy luminosity, and this will likely require extending the analysis to higher redshift. It is worth noting that this result does not rule out the merger hypothesis for the triggering of QSOs as Percival et al. (2003) have shown that halo merger sites are clustered the same as non-merger halos in N-body simulations. It is also possible to use objects from the SDSS and 2dFGRS galaxy surveys that are shown from their spectra to be AGN, as demonstrated recently by Miller et al (2003).

4. Discussion and future directions

QSO clustering measurements are starting to place interesting constraints on models of QSO formation. In particular it appears that lifetimes must be short, $\sim 10^6 - 10^7$ years. It is worth noting that the clustering measurements are in fact being used as a surrogate for host galaxy mass. In high redshift QSOs it is very difficult to make good estimates of galaxy mass, simply because the QSO luminosity dwarfs the host galaxy. If the observed relation between galaxy mass (or more exactly galaxy velocity dispersion) and black hole mass (M_{BH}) at low

redshift (e.g. Magorrian *et al.* 1998) is the same at high redshift then clustering can also be used to determine the mean M_{BH} for a population. However, it is likely that the local galaxy- M_{BH} relation does evolve with redshift. Clustering gives one potential method to determine if this is the case. The SDSS spectra are of sufficient quality that they should yield reasonable estimates of M_{BH} , thus allowing us to measure clustering as a function of M_{BH} .

New surveys are also required to break the still apparent luminosity-redshift degeneracy in QSO samples. We have very little knowledge of QSOs more than ~ 1 mag fainter than M^* , particularly at high redshift. A new survey based on SDSS imaging and 2dF spectroscopy is currently underway to address this issue and others, reaching a limiting magnitude of $g' \simeq 22$ for ~ 10000 QSOs. This is being carried out in tandem with a search for luminous red galaxies at $z < 0.7$, which will allow the investigation of QSO environments in 3D to much higher redshifts than currently possible. This, in combination with the high quality spectral information available from the SDSS should allow major progress in our understanding of QSO formation and evolution in the near future.

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